AFOSR-TR- 81-0404

January 1981 LEVEL II 014306-F

MICROWAVE SEMICONDUCTOR MATERIALS AND DEVICES

AD A098112

FINAL REPORT

ON

RESEARCH GRANT NO. AFOSR-76-2939

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) (14) Ø14306-F

(19) REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (18) AFOSR-TR-81-Ø4Ø4 ✓	2. GOVT ACCESSION NO. AD-A098112
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) MICROWAVE SEMICONDUCTOR MATERIALS AND DEVICES.	5. TYPE OF REPORT & PERIOD COVERED (9) Final rept. 1 Nov [redacted] 79-Dec [redacted] 1980
	6. PERFORMING ORG. REPORT NUMBER (31)
7. AUTHOR(s) (10) P. A. Blakey J. Chen J. R. East R. K. Froelich R. O. Grondin G. I. Haddad, B. L. Mattes	8. CONTRACT OR GRANT NUMBER(s) (15) AFOSR-76-2939 ✓
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electron Physics Laboratory The University of Michigan Ann Arbor, MI 48109 (17) C1	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) 2305-C1 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Major Clarence Gardner Air Force Office of Scientific Research Bolling AFB, DC 20332 1NF	12. REPORT DATE (11) Janu[redacted]981
	13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 33	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

High-frequency device modeling
IMPATT
MITATT
TUNNETT
BARITT photodetectors
Video detectors
Epitaxial growth
Honeycomb

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this program was to carry out fundamental studies in semiconductor materials and devices which are suitable for improving the state of the art in microwave and millimeter-wave power generation, amplification and detection. During the past year there were several active tasks under this program. A summary of each task is included in this report.

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LIST OF ILLUSTRATIONS

LIST OF PUBLICATIONS

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Professor G. I. Haddad, Project Director
Dr. Peter A. Blakey, Adjunct Research Scientist
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1977, H. Nguyen-Ba, Ph.D., "Properties and Applications of BARITT Devices."

1977, P. E. Bauhahn, Ph.D., "Properties of Semiconductor Materials and Microwave Transit-Time Devices."

1978, M. E. Elta, Ph.D., "The Effect of Mixed Tunneling and Avalanche Breakdown on Microwave Transit-Time Diodes."

INTERACTIONS (COUPLING ACTIVITIES)

Talks Given to Government and Industrial Organizations

Professor Haddad gave lectures on microwave and millimeter-wave devices at the following organizations:

1. Avionics Laboratory, Wright-Patterson Air Force Base. Hosts: Mr. Mark Calcaterra, Captain Alan Mertz and Captain Jon E. Grigus.

2. Hughes Aircraft Company, Canoga Park, CA. Host: Mr. Robert Eisenhart.

3. Hughes Research Laboratories, Malibu, CA. Hosts: Dr. Charles F. Krumm and Dr. P. K. Vasudev.

4. Microwave Associates, Burlington, MA. Hosts: Drs. T. B. Ramachandran and F. A. Brand.

5. Omni Spectra, Inc., Tempe, AZ. Hosts: Messrs. J. Cheal and C. Bissegger.

6. Naval Research Laboratory, Washington, DC. Host: Dr. B. Spielman.

Mr. Jack East, a research engineer on the project, has held discussions concerning this work with the following individual:

1. Dr. M. E. Elta, MIT, Lincoln Laboratory, Lexington, MA.

MICROWAVE SEMICONDUCTOR MATERIALS AND DEVICES

1. Introduction

The purpose of this program was to investigate semiconductor materials and devices for the generation, amplification, detection and control of electromagnetic radiation at microwave and millimeter-wave frequencies. The program consisted of theoretical and experimental work on various types of devices and the work performed during the last year is summarized in the following sections of this report. In particular, the following sections include the work done on:

1. Submicron device modeling.
2. IMPATT device modeling at millimeter wavelengths.
3. Noise in solid-state transit-time devices.
4. GaAs material growth for use in device fabrication.
5. TUNNETT and BARITT device fabrication and evaluation.

2. Submicron Device Modeling

2.1 Introduction. Virtually all analysis of semiconductor devices is based on obtaining solutions to the electron and hole continuity equations and Poisson's equation subject to appropriate boundary conditions. This is the quasi-free-particle (QFP) or band theory approximation. The continuity equations contain particle current terms, and to proceed with a device model, assumptions must be made regarding the nature of these particle currents. The most usual, very well-known assumption is the drift-diffusion approximation in which particle currents are assumed to consist of a drift component, with a drift velocity determined by the local electric field, and a diffusion component related to particle concentration gradients.

Until recently the drift-diffusion approximation proved adequate in the sense that calculated results were generally in reasonable agreement with experimental results for particular structures. However, improvements in technology mean that ever smaller devices become technologically feasible and devices with submicron dimensions can now be made. It is known that in the limit of small dimensions the drift-diffusion approximation becomes poor, and that for devices with submicron dimensions it is desirable to have available more general models to complement the existing drift-diffusion models. This phase of the program was devoted to developing such models. The progress made in this area during the past year is described here.

2.2 Work During the Past Year. During the past year a framework was established for a variety of approaches within the quasi-free-particle approximation, but of greater generality than the drift-diffusion approximation. A fairly detailed presentation of this framework was given in Reference 1, an invited contribution to a series on microstructure science and technology, and so details are not repeated here. Briefly, two important approaches are (1) statistical (Monte Carlo) simulation of transport processes, and (2) inclusion of energy and momentum (as well as particle) conservation in deterministic simulations of semiconductor devices. The statistical simulation can be used to obtain parameters required in the deterministic simulations.

Considerable progress has been made in both the above areas. A series of Monte Carlo simulation programs applicable to electron transport in compound semiconductors was written and used to obtain a variety of useful results. Also, an IMPATT simulation which includes carrier energy and momentum conservation effects was successfully

developed. This section outlines the status of the Monte Carlo simulation effort and the next section describes the energy and momentum conserving IMPATT simulation.

Three Monte Carlo simulation programs were written. The underlying model, applicable to electron transport in compound semiconductors (such as InP and GaAs), is the Fawcett two-valley model.[2,3] The three programs each incorporate the same scattering processes (acoustic phonon scattering, polar optical phonon emission and absorption, equivalent and nonequivalent intervalley scattering and ionized impurity scattering) but differ in the output they provide. Each program is coded with the aim of providing the particular output with maximum efficiency and all seem to be extremely more computationally efficient than Monte Carlo simulation programs of carrier transport developed by other groups. The simplest program, Version 1, outputs the electron state and time of flight at each collision. It provides a very efficient way of calculating "static" (constant field) transport parameters using B-ensemble estimation procedures.[4] The next version, Version 2, outputs the electron state at constant user-specified intervals Δt for $n(\geq 1)$ electron flights. This version is particularly useful for time-series analysis and for many-electron-ensemble-type estimation (such as for velocity overshoot calculations). It can handle a step function change in field. Version 3 is set up to permit arbitrary dc and periodic RF fields and is set up to calculate the RF admittance. The present effort is believed to represent the first time that a Monte Carlo simulation was sufficiently efficient to permit this large-signal RF admittance type of calculation.

All three programs proved useful to the modeling efforts. Version 1 is used for calculating static transport parameters, such as drift velocities and diffusion coefficients, for use in drift-diffusion simulations. It is also used for calculating momentum and energy relaxation times and intervalley scattering times, as functions of energy. These data are useful in energy and momentum conserving device simulations. Version 2 was used for calculation of velocity overshoot effects and in estimation of velocity fluctuation noise at millimeter- and submillimeter-wave frequencies.[5,6] Version 3 was used to calculate the frequency, signal level, and doping dependence of the RF admittance of N-type compound semiconductors.[7,8]

2.3 Conclusions and Suggestions for Further Work. A framework of approaches for modeling submicron semiconductor devices was established. A key stage of implementing this framework, establishment of techniques and computer programs for statistical simulation of carrier transport in semiconductors, was achieved. Monte Carlo simulations of electron transport in compound semiconductors were written which are extremely efficient compared to those available to other groups and which provide a variety of outputs well suited to efficient production of a variety of derived data.

Future work falls into two categories, exploitation of present facilities and extension of present facilities. Exploitation involves calculating more of the types of results already obtained to provide a fuller characterization of transport properties as functions of material, doping, temperature, bias, and RF fields, etc. This is straightforward, requiring only funding. The extensions would require significant additional work. First, the techniques should be extended

to covalent semiconductors to provide simulations of materials such as silicon and germanium. Methods for doing this are well known, established, and available[9] and would involve substantial modification of existing programs rather than development of new ones. Second, the techniques should be extended to hole transport. This also involves substantial modification of the existing programs rather than the development of completely new programs. Finally, the programs should be modified to give a better description of high fields. At the moment the simulations are of limited use at fields above approximately 20 kV/cm (in GaAs) because (1) only the valleys, not the full complete energy vs. momentum characteristic is modeled, and (2) the intracollisional field effect is neglected. Both of these effects should be modeled to obtain a useful treatment of various high-field processes important in transit-time devices. However their incorporation represents a major undertaking which would require significant support.

3. Millimeter-Wave IMPATT Device Modeling

3.1 Introduction. This phase of the program was concerned with developing and applying a computer model for millimeter-wave silicon IMPATT diodes. Results from the model will serve two primary purposes. First, they will give a prediction of the upper frequency limit on the performance of silicon IMPATT oscillators. Second, they will be useful in developing diode design rules for the best millimeter-wave performance. In addition, while computer models for IMPATT diodes already exist, they are based on a physical model which is expected to lose validity at millimeter-wave frequencies. The new model should have much wider validity and will hopefully provide a basis for determining where the existing models begin to break down.

3.2 Work Performed During the Past Year. Work on millimeter-wave device modeling began with a review of semiconductor physics and the development of a better physical model for device operation than has been used previously. A computer simulation, based on the resulting model, is now in operation. The remainder of this section outlines the development of the model and presents results from the simulation.

The starting point for device modeling is the equation describing electron transport in phase space:

$$\frac{\partial n}{\partial t} + \overline{v}\cdot\nabla n + \overline{a}\cdot\nabla_v n = \left(\frac{\partial n}{\partial t}\right)_c \quad . \tag{3.1}$$

The concentration $n = n(\overline{r},\overline{v},t)$ is a function of space and velocity coordinates. The left-hand side of the equation is the full-time derivative of n with respect to phase coordinates. The right-hand side represents changes in n due to discontinuous collision processes. This equation must be solved in general by random-flight (e.g., Monte Carlo) techniques. However, the problem can be simplified somewhat by using it to derive transport equations for velocity-averaged concentration, momentum, and energy in coordinate space. Taking the first three velocity moments of the equation results in the "hydrodynamic" equations,[10] which are the basis of the new model:

$$\frac{\partial N}{\partial t} + \nabla\cdot(N\overline{u}) = G \quad , \tag{3.2}$$

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\cdot\nabla\overline{u} - \frac{e\overline{E}}{m^*} + \frac{2}{3m^*N}\nabla\left(Nw - \frac{m^*}{2}Nu^2\right) = -\frac{\overline{u}}{\tau_u} \tag{3.3}$$

and

$$\frac{\partial w}{\partial t} + \overline{u}\cdot\nabla w - e\overline{u}\cdot\overline{E} + \frac{2}{3N}\nabla\cdot\left[N\overline{u}\left(w - \frac{m^*}{2}u^2\right)\right] = -\frac{w}{\tau_w} . \tag{3.4}$$

These three equations describe conservation of electron number, momentum and energy. N, $\overline{u}$, and w represent concentration, average velocity, and average energy in coordinate space. Effective velocity and energy lifetimes τ_u and τ_w are used to account for the effects of collisions.[11] The lifetimes, plus the ionization rates which enter into G, are taken to be functions of w.

Simplifying assumptions can be used to reduce the hydrodynamic equations to the conventional drift-diffusion model. First, a thermal energy can be defined by

$$\frac{3}{2}kT = w - \frac{1}{2}m^*u^2 . \tag{3.5}$$

Next, it is assumed that the thermal energy is constant in space and that $\overline{u}$ is everywhere in equilibrium with the electric field. Then the time partial and gradient of $\overline{u}$ can be ignored in the velocity equation giving

$$\overline{u} = \frac{e\tau_u}{m^*}\overline{E} - \frac{2}{3N}kT\tau_u\nabla N , \tag{3.6}$$

where $e\tau_u/m^*$ is mobility and $(2/3)kT\tau_u$ is a diffusion coefficient. Then

$$\overline{u} = \overline{s} - \frac{D}{N}\nabla N \tag{3.7}$$

and

$$\frac{\partial N}{\partial t} + \nabla\cdot(N\bar{s}) - \nabla\cdot(D\nabla N) = G \quad , \tag{3.8}$$

where $\bar{s}$ is the conventional drift velocity. Equation 3.8 is the drift diffusion model used in conventional diode simulations.

The energy and momentum conserving model is not complete without knowledge of the dependencies of τ_u, τ_w, and G on w. These can be found by examining the case of a steady-state, spatially uniform electric field. In this case, the time derivatives vanish and $\bar{u}$ and G become known functions of the electric field. $\tau_u(w)$, $\tau_w(w)$, and G(w) can then be inferred if a dc relationship between w and $\bar{E}$ is known. Several such relationships have been suggested in the literature; the work to date has incorporated one which was derived by Wolff.[12] This method of determining G and the lifetimes assures that, in the static limit, $\bar{u}$ and G will always take on their experimentally known dc values as functions of electric field.

In the course of developing a computer program based on energy and momentum conservation, one major problem had to be overcome. The simplest, explicit[13] finite-difference form of the model was found to be unstable except for very short time steps. In order to produce an economical simulation, it was necessary to find a way of allowing time steps to be longer. Bosch and Thim,[14] who applied energy and momentum conservation to the simpler problem of Gunn-diode modeling, suggested that exponential relaxation across each time step be used in place of the explicit formulation. They, however, used a quadratic approximation to the exponential which allows only a slightly longer time step. The simulation developed in this work retains the full exponential function, using table lookup to reduce

the cost of the exponential. This allows the use of a time step five to ten times longer than is permitted by the explicit form. With this technique, large-signal operating points can be evaluated in less than 10 s of CPU time on The University of Michigan Amdahl 470/V7 computer.

Figure 3.1 shows RF admittance data generated by the energy and momentum conserving simulation. The structure modeled is an n-type Schottky-barrier IMPATT with uniform doping and a length of 0.35 μm. Doping and dc current densities are 9×10^{16} cm^{-3} and 50 kA/cm^2, respectively. The RF amplitude is 5 V at each frequency.

3.3 Conclusions and Suggestions for Further Work. A practical computer simulation was developed which implements an improved physical model for silicon IMPATT diodes. The model is believed to give the best practical approximation to the phase space transport equation which is possible without requiring treatment of the random flights of individual electrons, as in Monte Carlo methods.

Extension of the model to compound semiconductor materials will require additional information about their properties. For silicon, lifetimes and generation rates as functions of carrier energy can be inferred from dc measurements of velocity and ionization rate as functions of electric field. In compound semiconductors, an energy and momentum conserving model must keep separate track of the lower- and upper-valley electron population.[11] Dc measurements lump together the contributions of the two populations to velocity and ionization rates, so the measurements do not provide enough information to infer separate lifetimes as functions of energy in each valley. Extension of existing Monte Carlo methods to larger dc electric fields could provide the needed extra information.

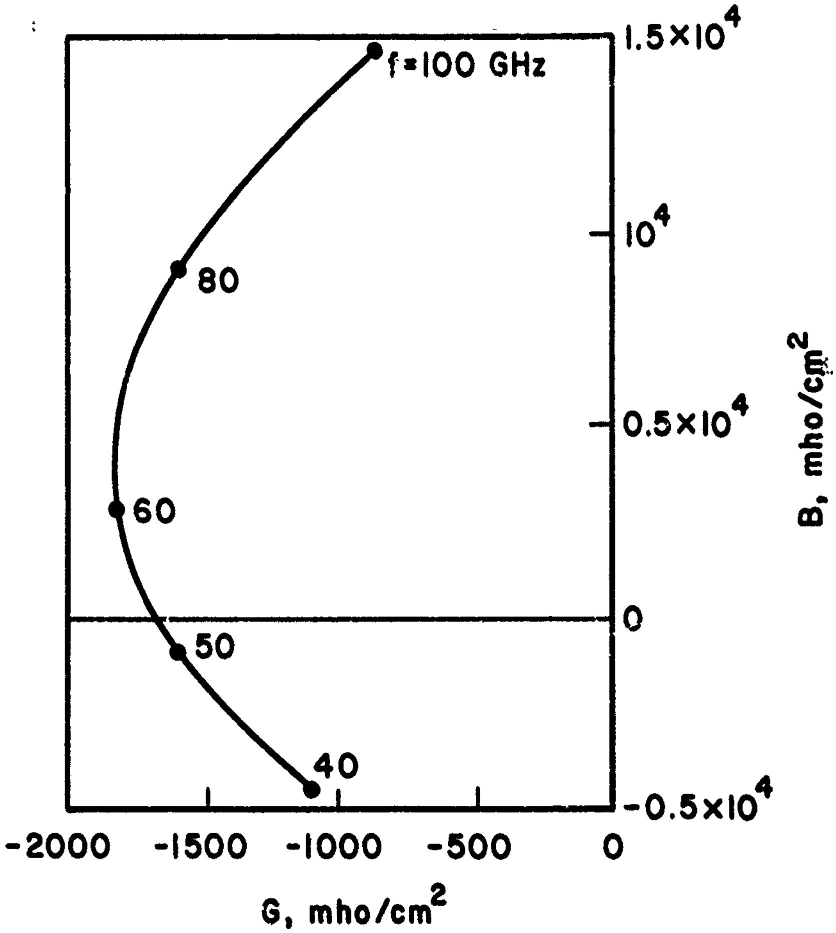

FIG. 3.1 ADMITTANCE OF SILICON IMPATT DIODE. (J_{dc} = 50 kA/cm^2, L = 0.35 μm AND N_d = 9 x 10^{16} cm^{-3})

The existing program may be readily applied to the investigation of millimeter-wave silicon IMPATTs. It will show where the drift-diffusion model breaks down due to relaxation effects and in what way. It is possible, for example, that energy relaxation will delay the avalanche injection of carriers in some IMPATT structures, resulting in better performance. The program can also be used to look for optimum millimeter-wave device designs. Finally, it will predict and show reasons for the ultimate frequency limitations on silicon IMPATT diodes.

4. Noise in Solid-State Transit-Time Devices

4.1 Introduction. The goal of this portion of the program was the development of methods useful in the modeling of noise in microwave and millimeter-wave transit-time devices. There are three steps involved in this noise characterization. The first is the development of an accurate characterization of the local microscopic fluctuations which create the noise. The second is a description of how these local fluctuations are transformed into noise currents and voltages at the device terminals. The last step is a description of the device-circuit interaction in oscillators and amplifiers as affected by this noise. In the last year the effort was directed on the first and third of these steps.

4.2 Work Done During the Past Year. There are four main microscopic noise sources in transit-time devices. These are avalanche noise, shot noise, velocity fluctuation noise, and thermal noise. The properties of avalanche and shot noise under large-signal conditions were described elsewhere.[15,16] Both are characterized

by being nonstationary and having significant correlation effects. These correlation effects are very important in IMPATT oscillators[17] and mixers.[18]

Velocity fluctuation noise (or diffusion noise) dominates BARITT device noise[19] and is expected to be very important in TUNNETTs. Since this noise is caused by the scattering induced microscopic fluctuations in the carrier velocity, it is possible to estimate the noise spectral density from Monte Carlo data. A sample result is shown in Fig. 4.1. Details of the estimation procedure are described elsewhere.[6] The Monte Carlo program described in Section 2 of this report was used in generating the data. Thermal noise can be viewed as the low field equilibrium limit of velocity fluctuation noise.

Once the terminal noise of the transit-time device is known it is possible to estimate the AM and FM noise under large-signal conditions in an oscillator by using a quasi-static oscillator model.[20,21] All previous estimates of the noise in transit-time device oscillators used such a model and an analytic model, such as the Read model, to predict the needed device parameters (such as impedances). A splining procedure was developed which allows a sophisticated computer model[22,23] to be used to generate these parameters. The basic quasi-static oscillator analysis was encoded into a FORTRAN computer program which is presently being used to evaluate the large-signal oscillator noise of TUNNETT devices. This approach should also be useful in evaluating the effect of rectification, tunneling, drift region ionization, premature collection, and other GaAs IMPATT diode parameters on oscillator noise and stability.

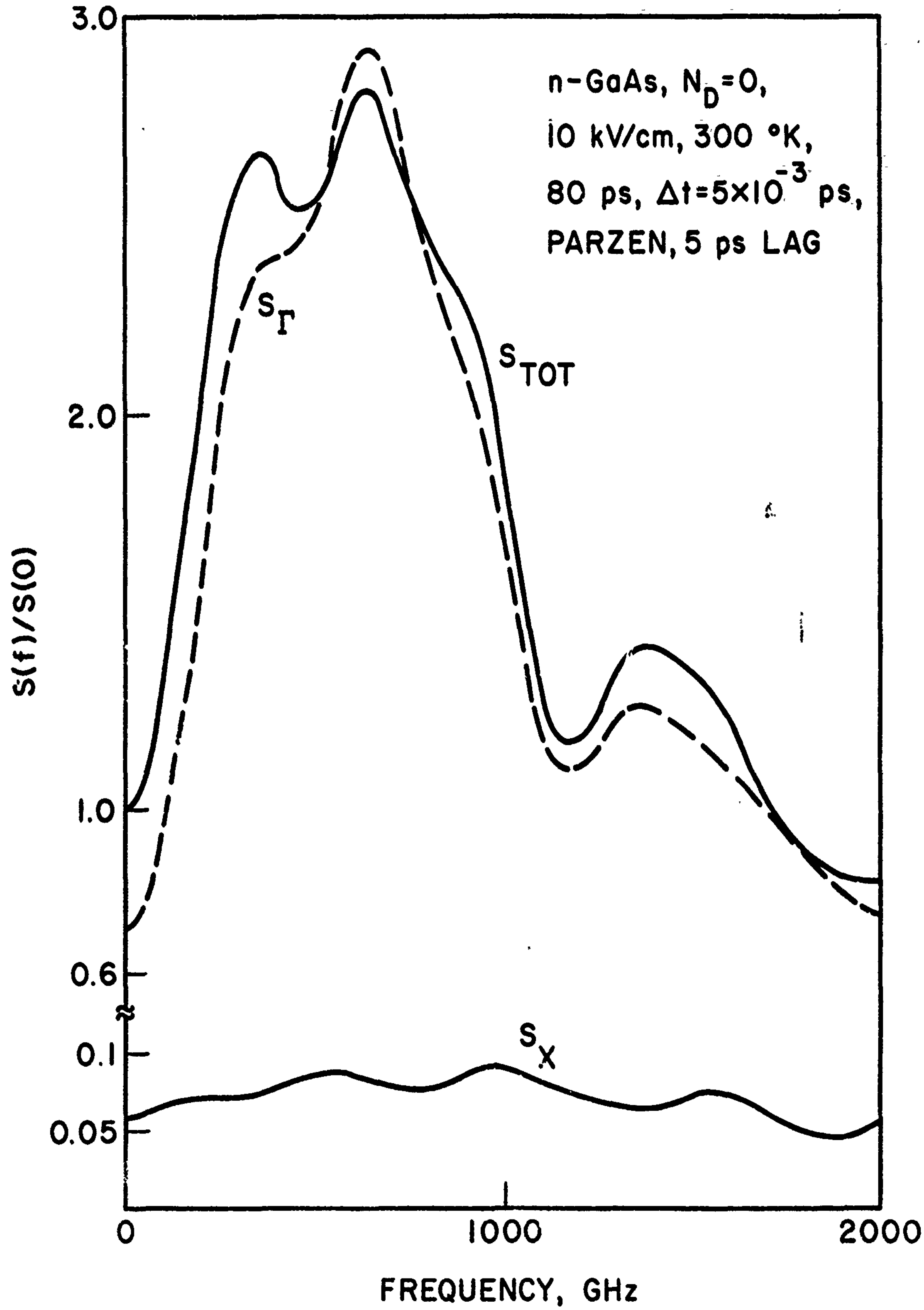

FIG. 4.1 SPECTRAL DENSITY OF VELOCITY FLUCTUATION NOISE IN GaAs.

5. GaAs Epitaxial Growth

5.1 Introduction. The purpose of this phase of the program was the growth of GaAs epitaxial material for microwave devices and, in particular, TUNNETT devices. Although epitaxial material was grown, problems with equipment and facilities prevented the fabrication of useful microwave device quality material. These problems and the present state of the material growth effort are discussed in the next section.

5.2 Summary of Results. The epitaxial material growth was slowed by two major time delays: the renovation of the laboratory space and the building of a small air-controlled room for the epitaxial reactors. During the delays the epitaxial reactor for growth was designed, built, cleaned and tested. Several epitaxial runs were made and layers grown. However there were problems making ohmic contacts to the surface. To solve this problem a small annealing furnace was designed and built. This allowed easy annealing of the indium ohmic contacts with the present facilities and equipment that have been built and tested. Unfortunately, it was not possible to obtain the proper epitaxial layers to fabricate useful TUNNETT devices. Even though the capability to do so exists now, it came too late for this program.

6. BARITT and TUNNETT Device Fabrication and Evaluation

6.1 Introduction. The purpose of this phase of the program was to design and fabricate BARITT and TUNNETT devices and to evalute them as oscillators and detectors. The work carried out on this phase of the program is summarized in the following section of this report.

6.2 Work During the Past Year. Earlier reports on this program discussed the fabrication of the "honeycomb" BARITT structure. Several problems with fabrication and packaging were described. During the past year most of these problems were solved and the major effort was in microwave testing of the devices. The fabrication problems involved photoresist step coverage problems with the device mesas. This problem was solved after testing a variety of photoresist combinations, pre- and postbake time, and etch processes. Most of the packaging problems occurred because a sharpless probe was being used to mount the diode in a small reduced height waveguide mount. The big advantage of this type of mount is low parasitics. However, given the equipment available, diodes could not be mounted reproducibly. The devices were then mounted in standard microwave packages using a thermocompression bonder. This type of packaging is much easier and produced good microwave results.

The BARITT devices were tested as video detectors at X-band frequencies. Their I-V characteristics, video impedance, TSS, dynamic range, and power burnout limitations were measured. The results show that the BARITT is equal to or superior to the Schottky detector in electrical properties. Because of its larger size for similar impedance level the BARITT should be easier to fabricate.

A typical BARITT I-V characteristic is shown in Fig. 6.1. This figure shows one of the advantages of the "honeycomb" structure. An ideal Shottky diode has a linear log current vs. voltage curve (shown as a dashed line on the figure). Typically the current drops below the linear curve at higher currents due to series resistance. However the BARITT current increases relative to the linear current

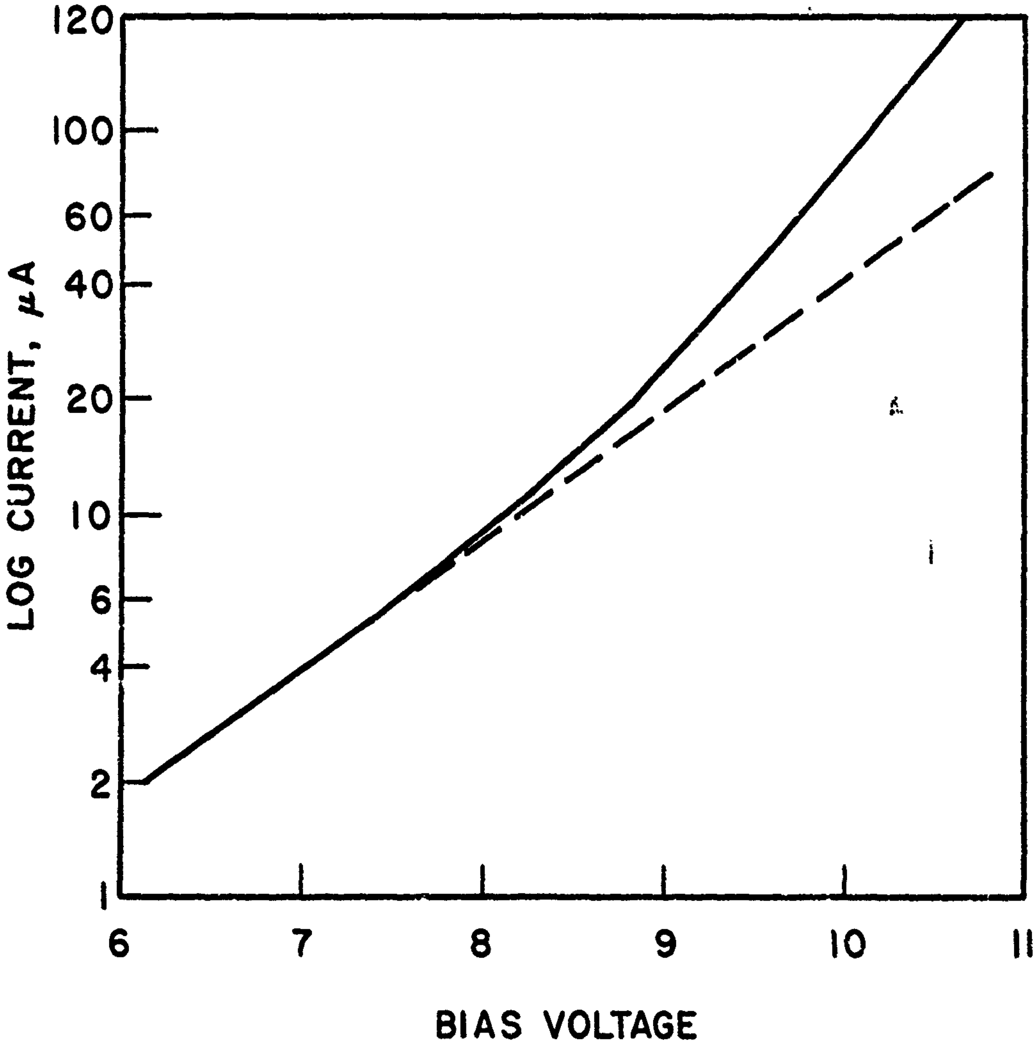

FIG. 6.1 BARITT DIODE I-V CHARACTERISTIC.

because of the two-dimensional nature of the current flow in the device. This reduces the effect of series resistance by spreading the current flow at higher current levels.

The video impedance of an X-band BARITT device is shown in Fig. 6.2. The behavior of the video impedance vs. current and incident power level is approximately the same as the Schottky-barrier detector.

The tangential sensitivity of the BARITT devices was measured at X-band (video bandwidth = 300 kHz, frequencies between 8 and 10 GHz). The best TSS measured was - 57 dBm. This compares well with the best X-band Schottky-barrier results. Typically TSSs were between - 50 and - 55 dBm.

The power handling ability of the BARITT device was measured by biasing the diode with the current that gave the best TSS. The incident power was then increased (CW) and the device operation measured. The results are shown in Fig. 6.3. The BARITT worked well up to the 10-W limit of the TWT used. Figure 6.3a shows the detected output voltage vs. input power for the device. The device dynamic range is approximately 45 dB. The power absorbed by the diode vs. incident CW power is shown in Fig. 6.3b and the rectified current vs. incident power is shown in Fig. 6.3c. The BARITT works well as a video detector over a wide dynamic range with no unusual effects at signal levels up to 10 W.

BARITT device fabrication for 18- to 40-GHz operation was also started. As a first try X-band devices were mounted into millimeter-wave minipill packages and the TSS measured from 20 to 40 GHz. The measured TSS was - 25 to - 30 dBm (video bandwidth = 300 kHz, f_o = 20 to 40 GHz). This is approximately 25 dB worse than the

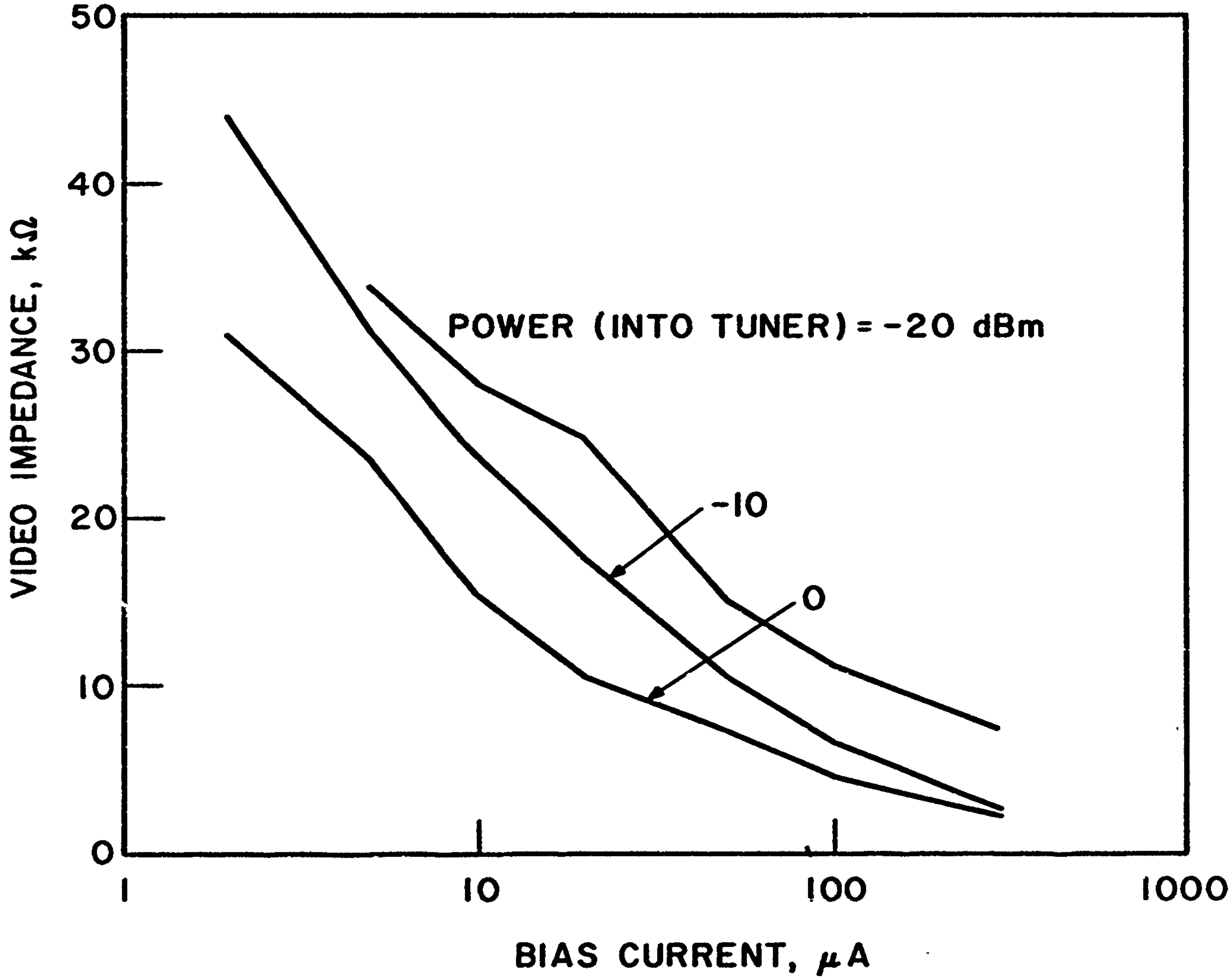

FIG. 6.2 VIDEO IMPEDANCE VS. CURRENT AND POWER LEVEL OF HONEYCOMB.

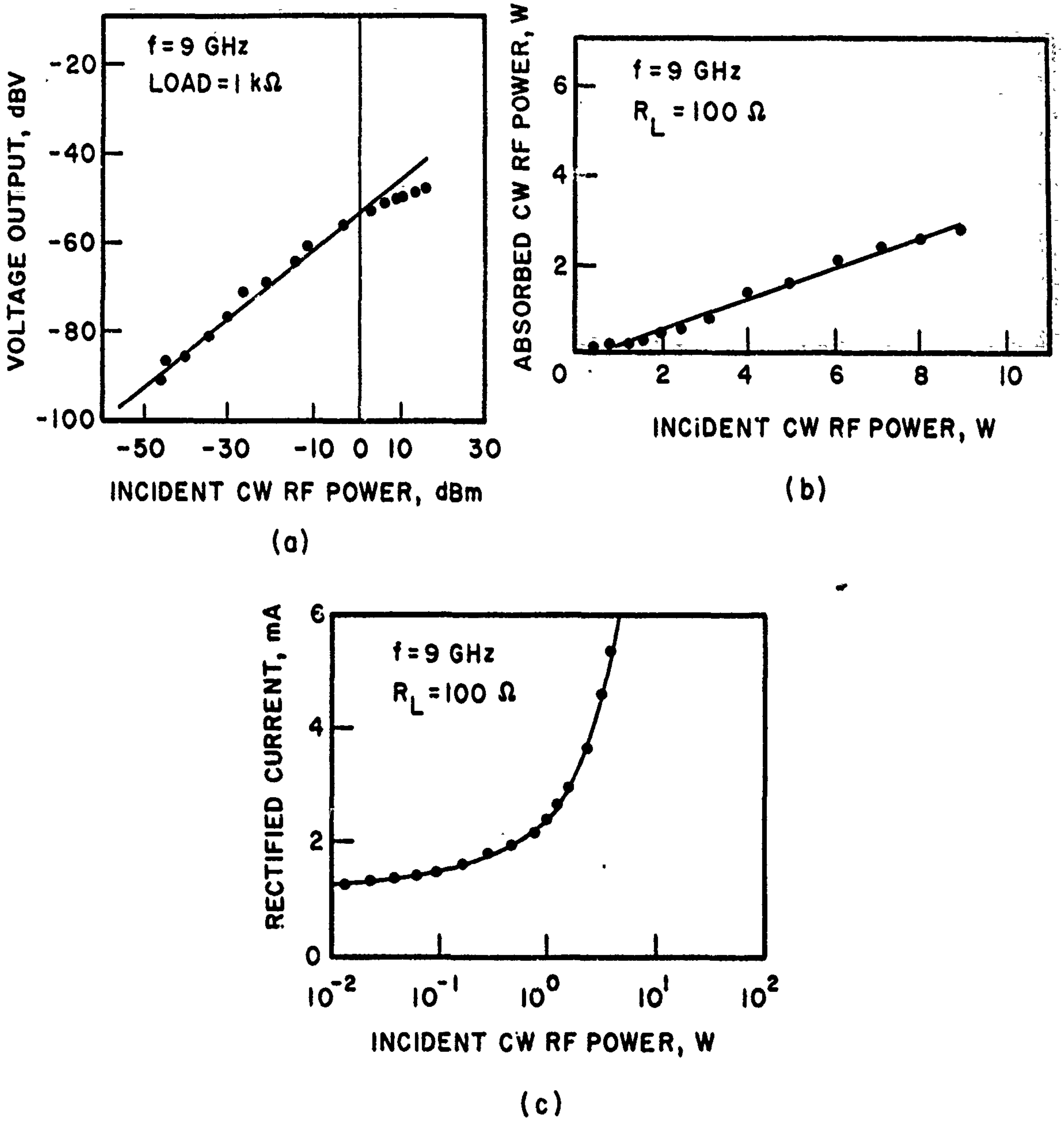

FIG. 6.3 (a) TYPICAL VOLTAGE OUTPUT VS. RF POWER FOR HONEYCOMB BARITT DIODE. (b) ABSORBED VS. INCIDENT CW POWER FOR X-BAND HONEYCOMB BARITT DIODE. (c) RECTIFIED CURRENT VS. INCIDENT RF POWER FOR X-BAND HONEYCOMB BARITT DIODE.

performance of the same diode at X-band. Additional wafers are presently being fabricated with a different doping profile hopefully to improve the millimeter-wave operation.

Since there was difficulty in obtaining proper material for TUNNETT devices, experimental work in this area was not carried out. It is believed, however, that the TUNNETT device has a great potential for millimeter-wave devices.

6.3 Summary. During the last year experimental results have shown the X-band BARITT diode video detectors are equal to or superior to Schottky-barrier devices. They have equal electrical properties and their larger size and silicon structure should make them easier to fabricate. Further work should improve the device operation in the 20- to 40-GHz and higher frequency range.

7. Summary of Major Accomplishments

There were several major accomplishments achieved under this program whose purpose was to improve the state of the art in microwave and millimeter-wave devices through investigation of novel devices and techniques. These accomplishments are described in detail in the various reports and publications issued under this program. Some of the main highlights are described briefly here.

1. IMPATT and TUNNETT Devices.

a. The most comprehensive computer program for the analysis of IMPATT devices available anywhere was developed under this program. It is now available to predict the properties of IMPATT devices for any material and doping profile. It includes ionization anywhere in the device, the proper velocity-electric

field characteristic and other important material parameters in an accurate manner with minimal computer time needed to obtain convergent solutions.

b. The effects of intrinsic response time on the properties of Si and GaAs devices were investigated and the various modes of operation which can exist for different avalanche or generation region widths were identified. The TUNNETT device was suggested as a possible source of power at millimeter wavelengths where reasonable amounts of power with fairly low noise operation can be obtained.

c. The use of heterojunctions in TUNNETT devices was suggested for improving the efficiency and power output by proper phasing of the induced current waveform.

d. Toward the latter part of the program the limitations and appl ability of the models for submicron dimensions and very high frequencies were examined by including energy and momentum relaxation effects to determine when these phenomena become important.

e. Estimates based on Monte Carlo simulations of hot carrier noise at millimeter- and submillimeter-wave frequencies have been obtained. This will be very important in determining noise performance in oscillators, detectors and mixers at these frequencies.

2. BARITT Devices.

a. A comprehensive theoretical and experimental program was carried out on BARITT devices.

b. It was shown that BARITT devices will be excellent in self-mixing doppler radar systems and are superior to any other device in this particular application.

c. BARITT devices were fabricated and tested up to approximately 40 GHz.

d. It was pointed out how the frequency of operation could be increased by utilizing certain doping profiles and the potential and capabilities of these devices were determined.

e. The effects of material parameters and doping profiles on the performance of these devices were established.

f. It was pointed out that BARITT devices will make excellent detectors and mixers with a fairly high burnout level and that they will be competitive with Schottky-barrier devices, particularly at millimeter wavelengths.

3. Epitaxial Growth of GaAs. During the latter part of this program equipment for liquid phase growth of GaAs epitaxial layers appropriate for millimeter-wave IMPATT, MITATT and TUNNETT devices was set up. It was hoped that with the proper material such devices could be fabricated in order to confirm the theoretical results. Because of several problems which arose during the program, the proper layers could not be obtained and thus the proper devices could not be fabricated. However, because of the work originating from this program several organizations, with a better materials capability than we have, are pursuing this work and encouraging experimental results are being obtained.

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